Precision Higgs Width at the ILC

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Based on Work with Tao Han and Zhen Liu

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Where Do We Go From Here?

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Junping will have already covered much of this.

We have a Higgs! (Or an unreasonable facsimile thereof...)

The LHC will continue to search for new physics in the form of SUSY, Extra Dimensions, Dark Matter, Additional Higgs, Z', W', 4^{th} Generation, etc., etc.

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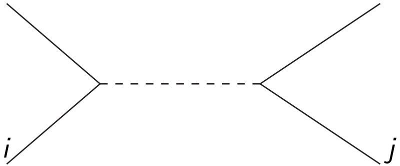
But there is a problem.

The Problem

We don't really measure g_i and Γ at the LHC. We measure processes of the form



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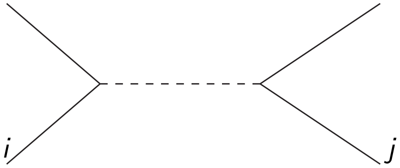


$$\sigma_{ij} \propto \frac{g_i^2 g_j^2}{\Gamma}$$

$$\forall i : g_i \to x g_i \qquad \Gamma \to x^4 \Gamma$$

Regardless of how many σ_{ij}s we measure.

Constraints are model dependent.

The Solution

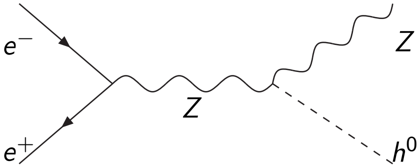
Measure $ii \to h \propto g_i^2$!

Break the degeneracy by measuring inclusive rates.

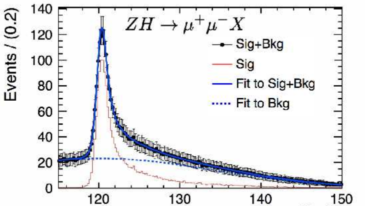
- But, virtually no way to do this at the LHC without assumptions.
- Can't rely on decay products.
- Instead use other particles in interaction to reconstruct a typical signature.
- Recoil mass to the rescue: $ii \to h + X$ then $M(ii - X) = M_h$
- Don't know initial states completely in a hadron collider, but we do at a lepton collider.

Recoil Mass at the ILC

At 250 GeV, we maximize Higgs production via "Higgstrahlung".



This allows a sharp mass peak (especially with $Z \to \mu\mu$) from which we can determine the cross-section $\delta\sigma_{Zh} \sim 2.5\%$. [Hengne Li, 2009]



Higgs Width Determination in General

By measuring the inclusive cross-section $\sigma_{Zh} \equiv \sigma(e^+e^- \to Zh)$ we can extract the coupling constant g_{hZZ} (to $\sim 1\%$).

We can use this to get the total width, and with that we can normalize all other couplings correctly and model independently. **All model independent width determinations depend on this measurement.**

The most straightforward way to calculate the total width:

$$\Gamma = \frac{\sigma_{ZH}^2}{\sigma_{ZZ}}$$

where $\sigma_{ZZ} \equiv \sigma(e^+e^- \to Zh \to ZZZ)$.

Unfortunately this is a rather hard measurement due to small cross-section.

For 250fb^{-1} at 250 GeV, $\delta_{ZZ} \equiv \frac{\Delta\sigma_{ZZ}}{\sigma_{ZZ}} \sim 20\%$. I.e. $\delta_\Gamma \sim 20 + \%$.

Generalizing

g_Z is our only independently measure coupling, so we need something proportional to $\frac{g_Z^n}{\Gamma}$. In practice $n = 4$ is our only choice. But, rather than:

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Or even a step further

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{ki}\sigma_{jl}}{\sigma_{Zi}\sigma_{Zj}\sigma_{kl}}$$

Combinations of Measurements

We can also benefit from averaging over equivalent combinations of measurements

$$\Gamma = \sigma_{ZH}^2 \left(\frac{1}{\sigma_{ZZ}} \oplus \sum_{i,j \neq Z} \frac{\sigma_{ij}}{\sigma_{Zi}\sigma_{Zj}}\right)$$

$$\Gamma = \sigma_{ZH}^2 \frac{\left(\frac{1}{\sigma_{ZZ}}\frac{1}{\delta_{ZZ}^2} + \sum_{i,j \neq Z} \frac{\sigma_{ij}}{\sigma_{Zi}\sigma_{Zj}} \frac{1}{(\delta_i z^2 + \delta_j z^2 + \delta_{ij}^2)}\right)}{\frac{1}{\delta_{ZZ}^2} + \sum_{i,j \neq Z} \frac{1}{\delta_{iZ}^2 + \delta_{jZ}^2 + \delta_{ij}^2}}$$

(But be careful when propagating errors.)

Also note that for some i, j, multiple processes can give us σ_{ij}.

$$\sigma_{WZ} = \sigma(Zh \to ZWW) \oplus \sigma(WW \to \nu\nu h \to \nu\nu ZZ)$$

In principle, we have many handles, although only some will be useful in terms of significance.

Expected Precisions

Energy	250 GeV	250 GeV	500 GeV	500 GeV
Process	$e^+e^- \to Zh$	$e^+e^- \to Z\nu\nu$	$e^+e^- \to e^+e^-h$	$e^+e^- \to Z\nu\nu$
δ_{Zb}	1.1%		1.8%	0.6%
δ_{ZW}	6.4%		9.2%	
δ_{Zc}	7.4%		12%	6.2%
$\delta_{Z\tau}$	4.2%		5.4%	14%
$\delta_{Z\gamma}$	$29-38\%$		$29-38\%$	$20-26\%$
δ_{Zg}	9.1%		14%	4.1%
δ_{Wb}		10.5%		0.6%
δ_{WW}				2.6%
δ_{Wc}				6.2%
$\delta_{W\tau}$				14.%
δ_{Wg}				4.1%

Numbers taken from DBD. Thanks to the work of many authors!

Optimum Channels

Clearly, b and W modes are dominant when accessible (for SM-like Higgs). But, at 250 GeV only some channels are available. We want to make maximum use of the data in hand.

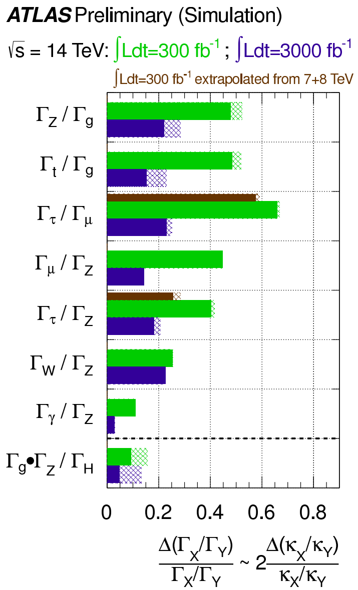
- σ_{ZZ} measurable but with poor precision expected. $\delta\Gamma \sim 20\%$.
- Need $\sigma_{ij} : i, j \neq Z$ for other routes. Durig et al. report σ_{Wb} measurable at 10% level. This is the only visible W-fusion channel at this energy, but it makes possible

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Wb}}{\sigma_{Zb}\sigma_{ZW}}$$
$$\delta\Gamma \simeq 13.4\%.$$

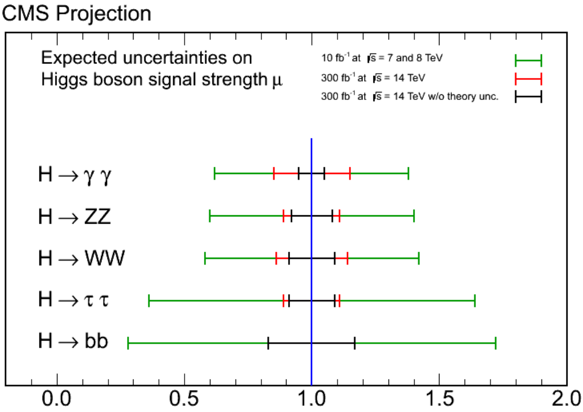
- This exhausts pure ILC options. However, we can turn to LHC data as well.

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Pi}}{\sigma_{PZ}\sigma_{Zi}}$$

LHC Branching Ratios, Atlas



LHC Higgs Couplings, CMS



250 GeV cont.

Useful LHC channels:

LHC Meas.	LHC Error (300/3000)	$\delta\Gamma$
$\frac{\Gamma_\gamma}{\Gamma_Z}$	12%/3%	32%/30%
$\frac{\Gamma_W}{\Gamma_Z}$	26%/22%	27%/23.5%
$\frac{\Gamma_\tau}{\Gamma_Z}$	40(26)%/18%	40(27)%/19%
$\frac{\Gamma_b}{\Gamma_Z}$	20%/?	21%/ ?

Multiple constraints contribute to best Γ at this energy.

$$\frac{\Gamma}{\sigma_{Zh}^2} = \sigma_{ZZ} \oplus \frac{\sigma_{WZ}\sigma_{bZ}}{\sigma_{Wb}} \oplus \frac{\sigma_{WZ}\sigma_{PZ}}{\sigma_{PW}} \oplus \frac{\sigma_{\gamma Z}\sigma_{PZ}}{\sigma_{P\gamma}} \oplus \frac{\sigma_{\tau Z}\sigma_{PZ}}{\sigma_{P\tau}} \oplus \frac{\sigma_{bZ}\sigma_{PZ}}{\sigma_{Pb}}$$

But pay attention to polarizations!

Typical polarization in studies is $P_{e^-}P_{e^+} = (-0.8, 3.0)$ needed for WW fusion. But opposite polarization used in $Zh->ZZZ, ZWW$ to suppress WW background.

Combined Result Estimates

Assuming numbers as given a combined analysis gives

$\delta_\Gamma \simeq 10/9\%$

However, the combination using $WW \to Zh \to Zbb$ uses left-handed polarized electrons. While the σ_{ZZ} and σ_{WZ} measurement rely on right-handed polarization to suppress background.

Using only LHC + right polarization

$\delta_\Gamma \simeq 13/11\%$

Options at 500 GeV

With full information from 500 GeV runs, the single best combination is likely to be

$$\Gamma = \sigma_{Zh}^2 \frac{\sigma_{Wb}^2}{\sigma_{Zb}^2 \sigma_{WW}}$$

- With 500fb^{-1} at 500 GeV,xpected relative error $\delta\Gamma \simeq 11\%$.
- Assuming full information from 250 and 500 GeV runs $\delta\Gamma \simeq 6\%$.
- However, the more direct route

$$\Gamma = \frac{\sigma_{ZH}^2 \sigma_{Wb}}{\sigma_{Zb} \sigma_{ZW}}$$

is potentially competitive. The key is optimizing σ_{ZW}.

Analysis of σ_{ZW}

We have carried out a fast simulation of $e^+e^- \to e^+e^-h \to e^+e^-ZZ$ and backgrounds.

Events generated using the ILC-Whizard setup provided by Mikael Berggren. Beam profiles generated by GuineaPig, Whizard 1.95 matrix elements, Pythia showering and hadronization, SGV3.0 detector simulation.

Test results compare well for $Zh \to \nu\nu bb$ done in full detector simulation by H. Ono.

Focus on $ZZ \to 4j$. Fully reconstructible final state.

Features many kinematic features to discriminate against background.

Limiting factor is total initial size. $N = 473$. Cuts must be **efficient**.

Summary of Results

Merge down to 4 hadron jets.
Primary cuts

1. Opposite sign ee
2. $70(110) < M_{ee} < 110(150)$
3. $110 < M_{rec} < 250$
4. $M_{4j} < 150$
5. $W_{off} < 70, 55 < W_{on} < 100$
6. $p_W^{hrest} < 45$
7. $L(\theta_j ..., Y_{34}, Y_{45})$

	Before Cuts		After Cuts	
	Zh	eeZ	$Z+X$	$ee+X$
Signal	158	315	85	183
$eeqq$	931500		65	100
$eeWW(4j)$	8750		2	9
$eeWW(2jl\nu)$	8390		1	9
$eeZZ/\gamma\gamma$	21235		37	76

$\delta\sigma(ee- > eeh, h- > WW- > 4j) = 8.8\%$

Adding in $Z \to \mu\mu$ conservatively

$\delta\sigma_{ZW} = 7.2\%$

Conclusions

- Using σ_{ZW} at 500 fb^{-1}, according to our simulations gives

$$\delta_\Gamma = 12\%$$

- Using full data from 250 and 500 yields

$$\delta_\Gamma = 6.5\%$$

- Combined with σ_{WW} data

$$\delta_\Gamma = 5.8\%$$

Conclusions

- ILC provides an ideal environment to assess Higgs width in model-independent way with high precision.
- 250 GeV run suggests multiple avenues to achieve best overall value.
- 500 GeV run can be dominated by a few well-studied modes. However, σ_{ZW} channels offer a competitive determination, and can be combined for best sensitivity.
- Further studies may bring more channels to prominence. Especially need improved $Zh- > ZZZ$ and LHC modes at 250.
- The future may hold surprises! All estimates based on SM-like branching fractions.